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Analysis of Tabun and Related Compounds by Packed Capillary Liquid Chromatography-Electrospray Mass Spectrometry (LC-ESI-MS)

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ABSTRACT

This study represents the first application of packed capillary column liquid chromatography-electrospray mass spectrometry (LC-ESI-MS) for the characterization of a munitions-grade chemical warfare agent, typical of what might be encountered during Canadian Forces (CF) sample collection. LC-ESI-MS was used for the direct analysis of nanogram quantities of tabun and eighteen related compounds in aqueous samples, extending the range of analytical options available to the researcher confronted with the identification of chemical warfare agents. Tabun and the related phosphates and pyrophosphates exhibited $(M+H)^+$, $(M+H+ACN)^+$ ions and/or protonated dimers that could be used to confirm the molecular mass of each compound. Product ions formed in the ESI interface were limited to those resulting from alkene loss from the alkoxy substituents (and their acetonitrile adducts). Additional product ion information were obtained following ESI-MS/MS analysis. The developed method appears to be an attractive alternative to gas chromatography-mass spectrometry (GC-MS) for the analysis of aqueous samples, since they may be analysed directly reducing the need for additional sample handling or derivatization steps.

EXECUTIVE SUMMARY

Title: "Analysis of Tabun and Related Compounds by Packed Capillary Liquid Chromatography-Electrospray Mass Spectrometry (LC-ESI-MS)", P.A. D'Agostino, J.R. Hancock and L.R. Provost, Technical Memorandum DRES TM 2000-004, 2000, UNCLASSIFIED.

Introduction: The Canadian Forces (CF) may be called on to perform peacekeeping or battlefield operations in regions of the world where there is a significant threat of chemical/biological (CB) warfare agent use. To operate effectively in these theatres the CF must be able to identify the CB agent used. Mass spectrometry (MS), is a powerful analytical technique for the identification of both known and unknown compounds and DRE Suffield is currently investigating this instrumental technique in fulfilment of CF detection and identification requirements.

Results: This study represents the first application of packed capillary column LC-ESI-MS for the characterization of a munitions-grade chemical warfare agent, typical of what might be encountered during CF sample collection. The developed packed capillary LC-ESI-MS method was successfully used for the direct detection and characterization of tabun and eighteen other phosphate and pyrophosphate compounds in a complex munitions-grade tabun sample. All the phosphates and pyrophosphates exhibited $(M+H)^+$, $(M+H+ACN)^+$ ions and/or protonated dimers that could be used to confirm the molecular mass of each compound. Product ions formed in the ESI interface were limited to those due to alkene loss from the alkoxy substituents (and their acetonitrile adducts). Additional product ion information were obtained by ESI-MS/MS. This approach appears to be an attractive alternative to GC-MS for the analysis of aqueous samples since it reduces the need for additional sample handling/derivatization and analysis steps.

Significance of Results: The CF may be deployed in regions of the world where there is a significant threat of chemical/biological warfare agent use. Identification of the CB agent is of importance since the results of such analyses would contribute to the development of strategic and political positions regarding future Canadian military operations and would facilitate the dissemination of technical advice to in-theatre field commanders and medical personnel.

Future Goals: The reported ESI-MS data could prove valuable for the identification of organophosphorus chemical warfare agents in samples collected by the Canadian Forces or in support of Chemical Weapons Convention challenge inspections.

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INTRODUCTION

The Canadian Forces (CF) routinely participates in peacekeeping and battlefield operations where exposure to chemical warfare agents (or other chemicals) may occur. Under this scenario, collection of representative samples by the CF would typically take place to confirm the identity of the chemical(s). Most recently, during the summer of 1999, the CF collected soil samples from locations in Croatia following reports of possible chemical warfare agent (or other chemical) exposure during Operation Harmony. These samples were then analysed by a number of specialist laboratories for the presence of chemical warfare agents and other chemicals of concern. Analyses of this type requires the use of sensitive, specific analytical methods, particularly when unambiguous proof is required for the prior presence of chemical warfare agents (1). These analytical demands are being actively addressed at Defence Research Establishment Suffield through the development and application of new analytical methods for the detection and identification of chemical warfare agents, their hydrolysis products and related compounds.

Gas chromatography (GC) has been used extensively for the separation and identification of the chemical warfare agents (1,2), with gas chromatography-mass spectrometry (GC-MS) being used most frequently for the characterization of these compounds (3-7). Organophosphorus chemical warfare agents, scheduled under the Chemical Weapons Convention, have been studied extensively by electron impact and chemical ionization mass spectrometry, as the use of these complementary ionization techniques facilitates the acquisition of molecular and fragmentation ion information that may be used for identification (8-10). GC separation, while suitable for the direct analysis of organophosphorus chemical warfare agent in organic

extracts, is usually not preferred for the direct analysis of aqueous samples. Aqueous samples containing organophosphorus chemical warfare agents and/or their nonvolatile hydrolysis products normally require additional sample handling steps and derivatization (11-13). Recently, water samples containing chemical warfare agents have been analysed by GC-MS following solid-phase microextraction (14) and by microcolumn liquid chromatography (LC) with flame photometric detection (15). Increasingly, researchers have developed LC-MS separation methods to deal with the analysis of aqueous samples containing these nonvolatile hydrolysis products (16-21). Benefits over GC analysis include reduced or no sample handling and no requirement for derivatization to enhance the volatility of the hydrolysis products.

Use of thermospray mass spectrometry (16-19) and more recently the atmospheric pressure ionization (e.g., electrospray (ESI), ionspray and atmospheric pressure CI) techniques (20-26) has enabled the direct mass spectrometric analysis of the hydrolysis products of organophosphorus chemical warfare agents. Both techniques may be interfaced to LC for component separation, with thermospray having been largely superseded by atmospheric pressure ionization (API). ESI-MS, the most sensitive technique for these applications (21), has only recently been applied to analysis of chemical warfare agents in aqueous samples (27,28). This paper focuses on the development and application of packed capillary LC-ESI-MS and ESI-MS/MS for the characterization of the chemical warfare agent, ethyl dimethylphosphoramidocyanidate (tabun or GA), its hydrolysis product and a number of related compounds in aqueous samples.

EXPERIMENTAL

ESI-MS and ESI-MS/MS data were acquired using a Micromass Autospec-Q tandem mass spectrometer equipped with the Mark II electrospray interface. The electrospray needle was operated at 7.6 kV and ions were accelerated into the mass spectrometer at 4 kV. Sampling cone voltages of 25 or 50 volts were utilized. Nitrogen bath gas was introduced into the interface (80 °C) at a flow rate of 300 L/h. Nitrogen nebulizer gas was introduced at a flow rate of 14 L/h. The electrospray interface was pumped with both a rotary and a turbomolecular pump, which enabled maintenance of 4×10^{-4} and 7×10^{-6} Pa within the source and analyser regions of the instrument, respectively. ESI-MS data were acquired in the continuum mode by scanning the magnetic sector from 600 to 60 u (7 s/decade) with a resolution of 1000 (10% valley definition). ESI-MS/MS data were acquired by selecting a precursor ion with the magnetic sector and scanning the quadrupole analyser from 275 to 60 u (3 s/scan). A quadrupole cell energy of 5 or 35 volts (laboratory scale) and an argon pressure of 1.5×10^{-4} Torr (near the cell) was used during all ESI-MS/MS acquisitions.

LC separations were performed using an Applied Biosystems Model 140B dual syringe pump equipped with a Zorbax 150 mm × 0.32 mm i.d. C_{18} SB (5 μm) packed fused-silica capillary column and a Rheodyne 8125 injector with a 5 μL sample loop. The following solvent compositions were prepared for sample introduction: Solvent A (0.1% trifluoroacetic acid in water) and Solvent B (0.1% trifluoroacetic acid in acetonitrile(ACN)/water, 95:5). Chromatographic separations were performed using a 1% to 75%B gradient program over 30 minutes. In order to minimize dead volume effects and ensure reproducible mixing, the mobile phase was delivered at 200 μL/min and split prior to the injector such that the flow

through the column was 11 μL/min.

Samples of relatively pure (90%) and munitions-grade tabun (approximately 70%) were provided by the Organic Chemistry Laboratory at Defence Research Establishment Suffield. Samples were prepared in water (pH 5 to 6) at concentrations ranging from 1 mg/mL to 0.01 mg/mL.

RESULTS AND DISCUSSION

GC-MS has been used extensively for the detection and identification of organophosphorus chemical warfare agents in organic extracts (1,2), but this separation method does not generally permit direct analysis of aqueous samples containing organophosphorus chemical warfare agents or their hydrolysis products. The development of a complementary LC-MS method for these compounds would be beneficial as it would allow simultaneous identification of both organophosphorus chemical warfare agents and their hydrolysis products in a single analysis based on both LC retention time and acquired MS data.

Collected environmental samples typically contain multiple components and require chromatographic separation prior to MS characterization of each individual component. An acetonitrile/water gradient program, from 1% to 75% B over 30 minutes, was developed as a good compromise between speed and resolution for the LC separation of the aqueous sample components. This method was demonstrated during LC-ESI-MS analysis of a complex munitions-grade tabun sample (Figure 1) and a relatively pure sample of tabun (Figure 2). Nineteen phosphates and pyrophosphate compounds, listed in Table I, were identified based on the mass spectrometric data acquired during LC-ESI-MS analysis of the

munitions-grade tabun sample. The acquired mass spectra contained $(M+H)^+$, $(M+H+ACN)^+$ ions and/or protonated dimers that could be used to confirm the molecular mass of each compound. Structural information was provided by inducing product ion formation in either the ESI interface or the quadrupole collisional cell.

The formation of significant acetonitrile (ACN) adducts was not anticipated. While this behaviour has been observed during some pharmaceutical analyses, it was not significant during a prior LC-ESI-MS study of mustard hydrolysis products (26) and VX (27). Adduct ion formation, similar to what has been observed for organophosphorus chemical warfare agents during ammonia CI-MS (9), was likely due to the lower proton affinity of the compounds coupled with the opportunity for multiple collisions within the ESI interface. The effect of the organic component in the mobile phase was investigated by replacing acetonitrile with methanol during gradient LC-ESI-MS analysis of the same munitions-grade tabun sample (Figure 3). The most notable change in the acquired mass spectra for tabun and related compounds in the sample was the presence of methanol as opposed to acetonitrile adducts. Finally the formation of these solvent adducts was also observed with two completely different mass spectrometers, a Hewlett Packard 1100 MSD (quadrupole) and a Micromass LCT (time-of-flight).

Table II and III list the mass spectra that were obtained for the nineteen phosphate and pyrophosphate compounds identified in the munitions-grade tabun sample. All the spectra exhibited $(M+H)^+$, $(M+H+ACN)^+$ ions and/or protonated dimers that could be used to confirm the molecular mass of each compound. The data presented were obtained with a sampling cone voltage of 50 volts, a setting that promoted collisions in the ESI interface and resulted in the formation of product ions. Product ions due to alkene loss from the alkoxy substituents, and the

acetonitrile adduct associated with these product ions, were generally observed.

Figure 4 illustrates the ESI-MS data acquired for tabun with an acetonitrile/water and methanol/water mobile phase. $(M+H)^+$, $(M+H+ACN \text{ or } MeOH)^+$ ions and the protonated dimer was observed at the lower sampling cone setting (25 V) with both mobile phases (Figure 4a and 4c). At a higher sampling cone setting (50 V), a product ion due to loss of C_2H_4 was observed for tabun (Figure 4b) at m/z 135, along with its acetonitrile adduct at m/z 176.

Figure 5 illustrates typical ESI-MS data for two phosphates and a pyrophosphate obtained at a sampling cone voltage of 50 V. Molecular mass was confirmed for all compounds based on the acquisition of $(M+H)^+$ and/or $(M+H+ACN)^+$ ions and product ions. Product ions, due to alkene loss from alkoxy substituents (and their acetonitrile adducts), were also observed. Triethyl phosphate (Figure 5a) exhibited product ions at m/z 99 (weak), m/z 127, and m/z 155 due to sequential loss of ethylene from the protonated molecular ion. The corresponding acetonitrile adducts were also observed at m/z 140, m/z 168 and m/z 196, respectively. Ethyl isopropyl dimethylphosphoramidate (Figure 5b) exhibited loss of both C_3H_6 and C_2H_4, indicative of a compound with both isopropoxy and ethoxy substitution. The corresponding acetonitrile adducts were also observed at m/z 167 and m/z 195. Product ions due to sequential loss C_3H_6 (m/z 234 and m/z 276) and an acetonitrile adduct (m/z 275) were observed for the pyrophosphate, diisopropyl phosphoric ethyl dimethylphosphoramidic anhydride (Figure 5c).

ESI-MS/MS was investigated as a complementary technique for the acquisition of structural data for tabun (Figure 6) and a common phosphate, triethyl phosphate (Figure 7). The product ion mass spectra obtained for the protonated

acetonitrile adduct of tabun and the acetonitrile adduct of m/z 135 (at m/z 176) both contained ions due the loss of acetonitrile, confirming its presence in the ion structure. The energy required to induce product ion formation was minimal (5 V, laboratory scale), indicative of an a weakly associated adduct structure. Product ion formation for the protonated molecular ion of tabun (Figure 6c) required considerably more energy (35 V, laboratory scale). More structural information were obtained during ESI-MS/MS analysis than by simply inducing product ion formation in the ESI interface. Product ions at m/z 135, m/z 117 and m/z 108, due to $(MH-C_2H_4)^+$, $(MH-C_2H_4-H_2O)^+$and $(MH-C_2H_4-HCN)^+$, were observed, indicative of a compound containing both ethoxy and cyano substitution.

The ESI-MS/MS data obtained for the protonated acetonitrile adduct of triethyl phosphate (Figure 7a) and the acetonitrile adduct of m/z 155 (at m/z 196) (Figure 7b) both contained ions due the loss of acetonitrile, confirming its presence in the ion structure. The energy required to induce product ion formation was again minimal (5 V, laboratory scale). Product ion formation for the protonated molecular ion of triethyl phosphate (Figure 7c) required considerably more energy (35 V, laboratory scale). Product ion information obtained during ESI-MS/MS were again more informative than those generated by simply inducing product ion formation in the ESI interface. Product ions at m/z 155, m/z 127 and m/z 99, due to sequential loss of ethylene, were observed, confirming triethoxy substitution.

A detailed detection limit study was not undertaken as the study focussed more on the separation and characterization of the organophosphorus chemical warfare agents. A full scanning (600 to 60 u) detection limit of 1-5 ng, based on the acquisition of an interpretable mass spectrum, was estimated during analysis of the 0.01 mg/mL standard mixture and a relatively pure tabun standard with the

same concentration (Figure 2). This limit was similar to that obtained during the analysis of organophosphorus chemical warfare agents by GC-MS with the same instrument (500 pg to 1 ng). Selected-ion-monitoring, which typically results in a 10 to 100 fold increase in sensitivity, was not evaluated.

CONCLUSIONS

Packed capillary column LC-ESI-MS was used for the characterization of a munitions-grade chemical warfare agent, typical of what might be encountered during CF sample collection. LC-ESI-MS was used for the direct analysis of nanogram quantities of tabun and eighteen related compounds in aqueous samples, extending the range of analytical options available to the researcher confronted with the identification of chemical warfare agents. The developed method appears to be an attractive alternative to GC-MS for the analysis of aqueous samples since they may be analysed directly reducing the need for additional sample handling or derivatization steps.

ESI-MS data were collected with sampling cone voltages in the 25 to 50 volts range. In general the most informative mass spectra were acquired with the higher sampling cone voltage. All the phosphates and pyrophosphates exhibited $(M+H)^+$, $(M+H+ACN)^+$ ions and/or protonated dimers that could be used to confirm the molecular mass of each compound. Product ions due to CAD in the ESI interface were limited to alkene loss from the alkoxy substituents (and their acetonitrile adducts). Additional product ion information were obtained following ESI-MS/MS analysis.

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Table I: Compounds identified during LC-ESI-MS analysis of tabun. Structures are listed in Tables II and III with corresponding ESI-MS data.

Peak No.[1]	Mol. Wt.	Compound Name
1	153	Ethyl hydrogen dimethylphosphoramidate
2	161	Tetramethylphosphodiamidic cyanide
3	162	Ethyl dimethylphosphoramidocyanidate (Tabun)
4	180	Ethyl tetramethylphosphoramidate
5	181	Diethyl dimethylphosphoramidate
6	182	Triethyl phosphate
7	288	Bis(ethyl dimethylphosphoramidic) anhydride[2]
8	289	Diethyl phosphoric ethyl dimethylphosphoramidic anhydride
9	195	Ethyl isopropyl dimethylphosphoramidate
10	290	Bis(diethyl phosphoric) anhydride
11	196	Diethyl isopropyl phosphate
12	303	Diethyl phosphoric isopropyl dimethylphosphoramidic anhydride[2]
13	304	Diethyl phosphoric ethyl isopropyl phosphoric anhydride
14	317	Diisopropyl phosphoric ethyl dimethylphosphoramidic anhydride[2]
15	210	Diisopropyl ethyl phosphate
16	318	Diethyl phosphoric diisopropyl phosphoric anhydride[2]
17	224	Triisopropyl phosphate
18	332	Diisopropyl phosphoric ethyl isopropyl phosphoric anhydride
19	346	Bis(diisopropyl phosphoric) anhydride

[1] Chromatographic peak number. Refer to Figure 1, 2 and 3.
[2] Or isomer.

Table II: ESI-MS Data (50 volts) for Phosphates with general structure $R_1R_2R_3P=O$

Ion Identity	m/z (% Relative Intensity) Chromatographic Peak Number followed by R_1, R_2 and R_3 (shown vertically)									
	1 OH OEt NMe_2	2 NMe_2 NMe_2 CN	3 OEt NMe_2 CN	4 OEt NMe_2 NMe_2	5 OEt OEt NMe_2	6 OEt OEt OEt	9 OEt O*i*Pr NMe_2	11 OEt OEt O*i*Pr	15 OEt O*i*Pr O*i*Pr	17 O*i*Pr O*i*Pr O*i*Pr
$(M_2H)^+$	307 (55)	323 (2)	325 (24)	361 (1)	363 (1)	365 (1)	391 (3)	393 (5)	421 (9)	449 (11)
$(MH+ACN)^+$	195 (3)	203 (87)	204 (100)	222 (5)	223 (8)	224 (30)	237 (10)	238 (27)	252 (26)	266 (21)
$(MH)^+$	154 (100)	162 (100)	163 (72)	181 (100)	182 (100)	183 (100)	196 (100)	197 (100)	211 (100)	225 (100)
$(MH-C_2H_4)^+$	126 (38)		135 (12)	153 (9)	154 (10)	155 (14)				
$(MH-C_2H_4+ACN)^+$	167 (4)		176 (44)	194 (2)	195 (3)	196 (19)				
$(MH-(C_2H_4)_2)^+$					126 (6)	127 (6)				
$(MH-(C_2H_4)_2+ACN)^+$					167 (5)	168 (21)				
$(MH-(C_2H_4)_3)^+$						99 (1)				
$(MH-(C_2H_4)_3+ACN)^+$						140 (9)				
$(MH-C_3H_6)^+$							154 (52)	155 (49)	169 (17)	183 (14)
$(MH-C_3H_6+ACN)^+$							195 (32)	196 (87)	210 (33)	224 (27)
$(MH-C_3H_6-C_2H_4)^+$							126 (8)	127 (7)		
$(MH-C_3H_6-C_2H_4+ACN)^+$							167 (13)	168 (24)		
$(MH-C_3H_6-(C_2H_4)_2)^+$								99 (2)		

Ion Identity	m/z (% Relative Intensity) Chromatographic Peak Number followed by R_1, R_2 and R_3 (shown vertically)									
	1 OH OEt NMe_2	2 NMe_2 NMe_2 CN	3 OEt NMe_2 CN	4 OEt NMe_2 NMe_2	5 OEt OEt NMe_2	6 OEt OEt OEt	9 OEt O*i*Pr NMe_2	11 OEt OEt O*i*Pr	15 OEt O*i*Pr O*i*Pr	17 O*i*Pr O*i*Pr O*i*Pr
$(MH-C_3H_6-(C_2H_4)_2+ACN)$								140 (12)		
$(MH-(C_3H_6)_2)^+$									127 (14)	141 (6)
$(MH-(C_3H_6)_2+ACN)^+$									168 (81)	181 (14)
$(MH-(C_3H_6)_2-C_2H_4)^+$									99 (1)	182 (43)
$(MH-(C_3H_6)_2-C_2H_4+ACN)^+$									140 (10)	
$(MH-(C_3H_6)_3)^+$										99 (5)
$(MH-(C_3H_6)_3+ACN)^+$										140 (38)
Additional Ions	460 (4) 199 (11)							415 (5)	443 (5)	471 (3)

Table III: ESI-MS Data (50 volts) for Pyrophosphates with general structure $R_1R_2P(O)\text{-}O\text{-}P(O)R_3R_4$

Ion Identity	m/z (% Relative Intensity) Chromatographic Peak Number followed by R_1, R_2, R_3 and R_4 (shown vertically)								
	7 OEt NMe_2 OEt NMe_2	8 OEt OEt OEt NMe_2	10 OEt OEt OEt OEt	12 OEt OEt O*i*Pr NMe_2	13 OEt OEt OEt O*i*Pr	14 OEt NMe_2 O*i*Pr O*i*Pr	16 OEt OEt O*i*Pr O*i*Pr	18 OEt O*i*Pr O*i*Pr O*i*Pr	19 O*i*Pr O*i*Pr O*i*Pr O*i*Pr
$(MH+HNMe_2)^+$	334 (4)	335 (4)	336 (5)	349 (4)	350 (6)	363 (4)	364 (5)	378 (6)	392 (7)
$(MH+NH_3)^+$	306 (1)	307 (2)	308 (3)	321 (3)	322 (6)	335 (5)	336 (10)	350 (8)	364 (4)
$(MH)^+$	289 (100)	290 (100)	291 (100)	304 (49)	305 (50)	318 (57)	319 (66)	333 (65)	347 (97)
$(MH-C_2H_4)^+$	261 (9)	262 (25)	263 (41)						
$(MH-C_2H_4+ACN)^+$		303 (2)	304 (6)						
$(MH-(C_2H_4)_2)^+$		234 (5)	235 (11)						
$(MH-(C_2H_4)_2+ACN)^+$		275 (3)	276 (18)						
$(MH-(C_2H_4)_3)^+$			207 (2)						
$(MH-(C_2H_4)_3+ACN)^+$			248 (10)						
$(MH-C_3H_6)^+$				262 (100)	263 (100)	276 (51)	277 (42)	291 (45)	305 (100)
$(MH-C_3H_6+ACN)^+$				303 (6)	304 (25)	317 (3)	318 (7)	332 (5)	346 (6)
$(MH-C_3H_6-C_2H_4)^+$				234 (7)	235 (8)				

Ion Identity	m/z (% Relative Intensity) Chromatographic Peak Number followed by R_1, R_2, R_3 and R_4 (shown vertically)								
	7 OEt NMe_2 OEt NMe_2	8 OEt OEt OEt NMe_2	10 OEt OEt OEt OEt	12 OEt OEt O*i*Pr NMe_2	13 OEt OEt OEt O*i*Pr	14 OEt NMe_2 O*i*Pr O*i*Pr	16 OEt OEt O*i*Pr O*i*Pr	18 OEt O*i*Pr O*i*Pr O*i*Pr	19 O*i*Pr O*i*Pr O*i*Pr O*i*Pr
$(MH-C_3H_6-C_2H_4+ACN)^+$				275 (5)	276 (21)				
$(MH-C_3H_6-(C_2H_4)_2+ACN)$				247 (2)	248 (10)				
$(MH-(C_3H_6)_2)^+$						234 (100)	235 (76)	249 (29)	263 (51)
$(MH-(C_3H_6)_2+ACN)^+$						275 (33)	276 (100)	290 (49)	304 (82)
$(MH-(C_3H_6)_2-C_2H_4)^+$							207 (1)		
$(MH-(C_3H_6)_2-C_2H_4+ACN)^+$							248 (13)		
$(MH-(C_3H_6)_3)^+$								207 (9)	221 (10)
$(MH-(C_3H_6)_3+ACN)^+$								248 (100)	262 (96)
Additional Ions	244 (13)				220 (3)				220 (34) 261 (24)

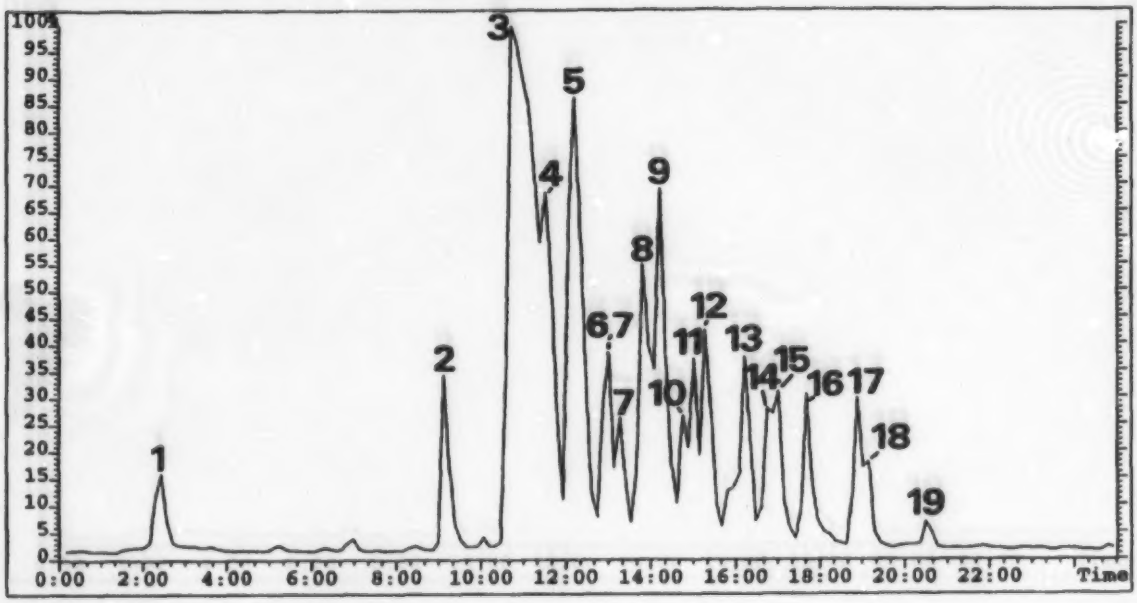

Figure 1: Packed capillary LC-ESI-MS total-ion-current (600 to 60 u) chromatogram obtained for tabun and related compounds (1 mg/mL) with an acetonitrile/ water mobile phase. Sample components are identified in Table I.

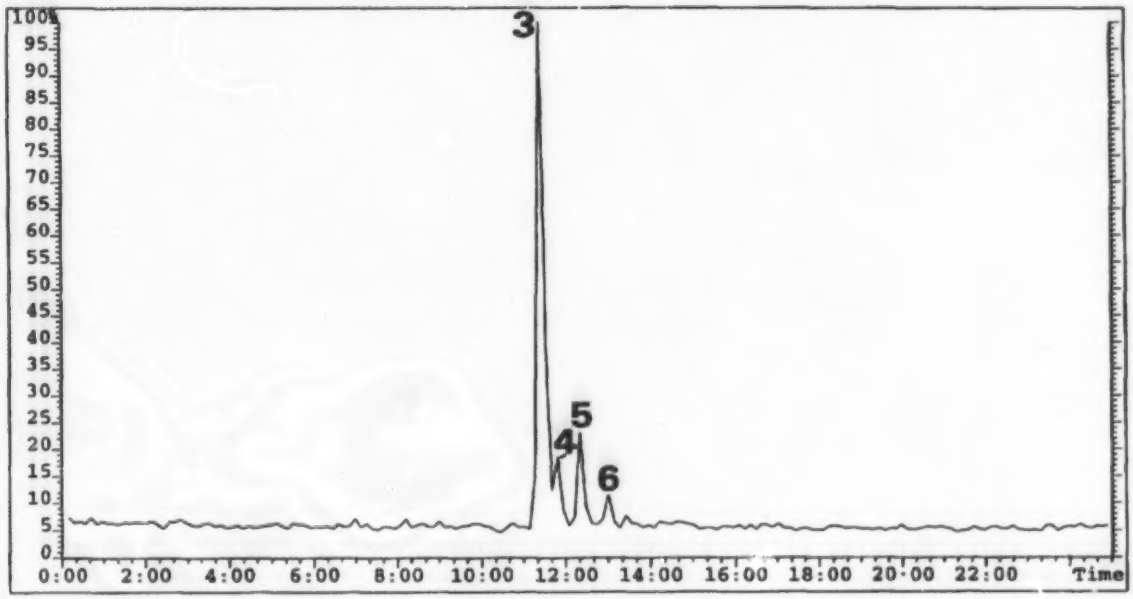

Figure 2: Packed capillary LC-ESI-MS total-ion-current (600 to 60 u) chromatogram obtained for a relatively pure tabun sample (0.01 mg/mL) with an acetonitrile/water mobile phase. Sample components are identified in Table I.

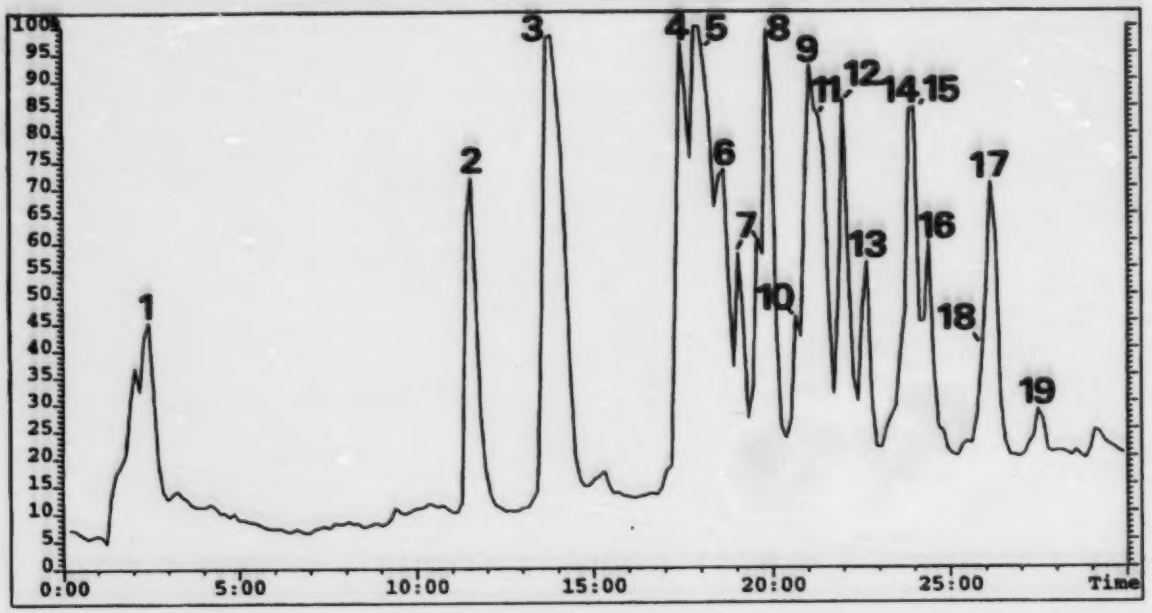

Figure 3: Packed capillary LC-ESI-MS total-ion-current (600 to 60 u) chromatogram obtained for tabun and related compounds (0.1 mg/mL) with a methanol/ water mobile phase. Sample components are identified in Table I.

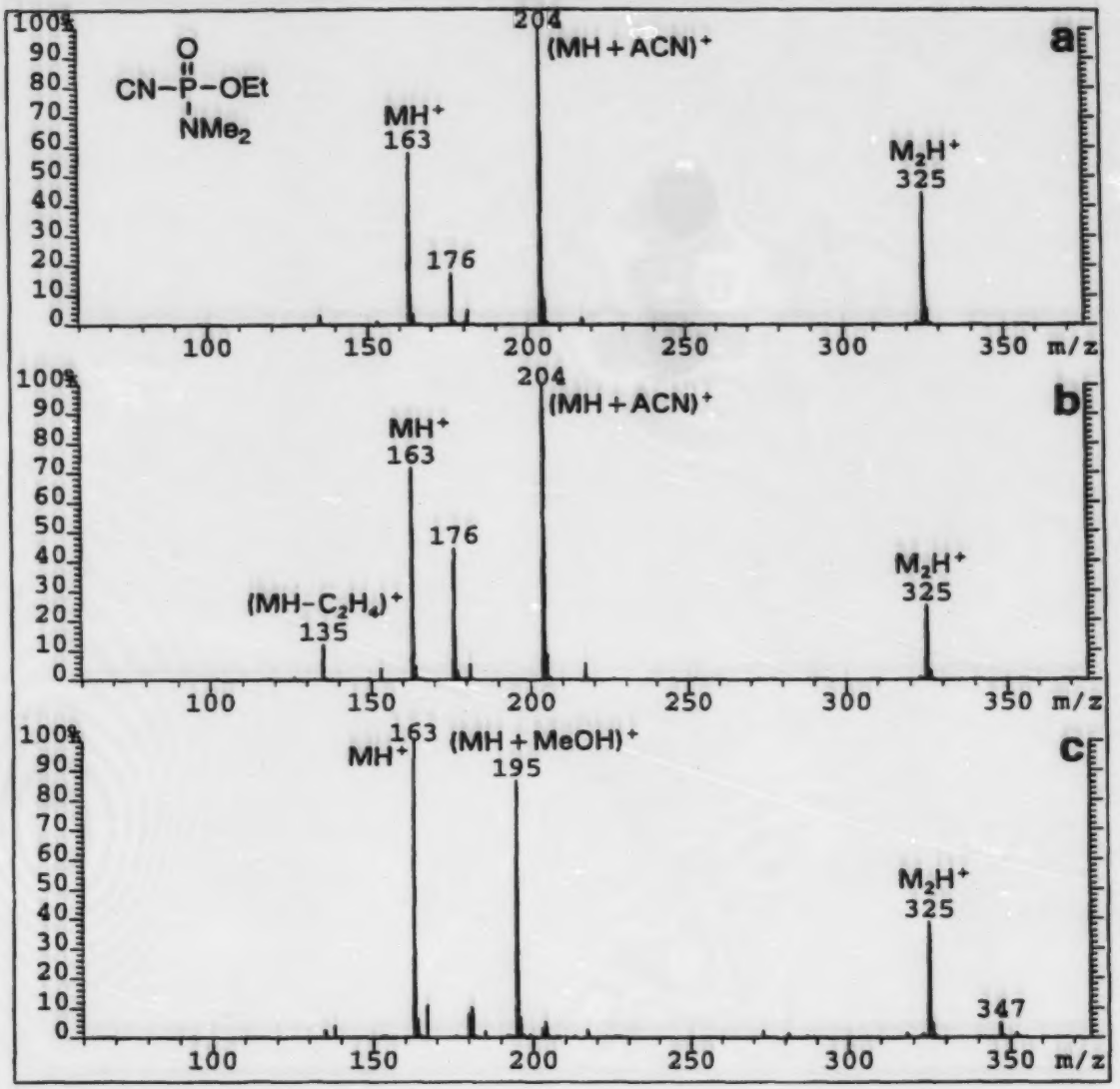

Figure 4: ESI-MS data obtained for tabun using an acetonitrile/water mobile phase and sampling cone voltages of a) 25 volts and b) 50 volts. ESI-MS data obtained for tabun using a methanol/water mobile phase and sampling cone voltage of c) 25 volts.

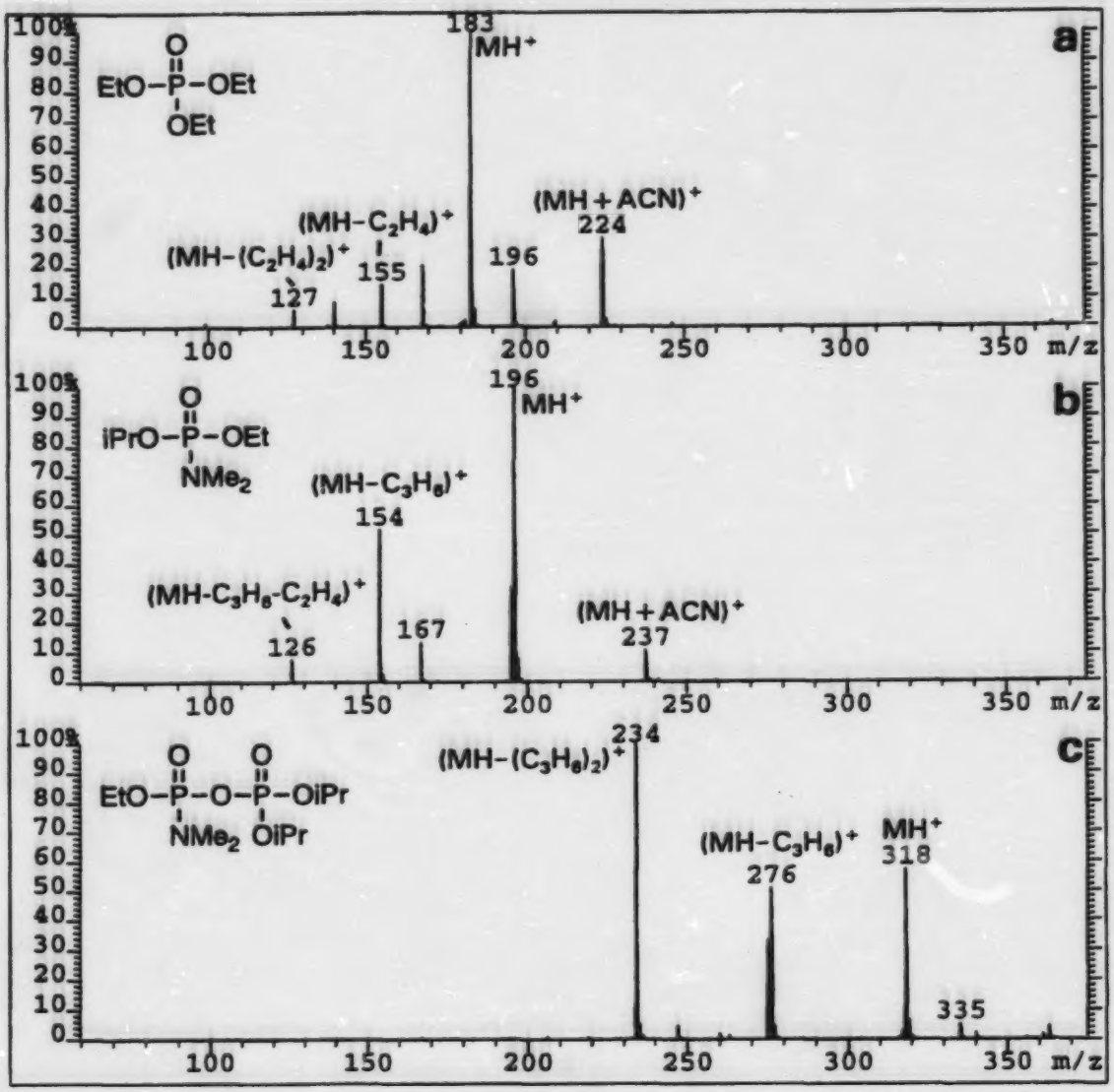

Figure 5: ESI-MS data obtained for a) triethyl phosphate, b) ethyl isopropyl dimethylphosphoramidate and c) diisopropyl phosphoric ethyl dimethylphosphoramidic anhydride using an acetonitrile/water mobile phase and sampling cone voltage of 50 volts.

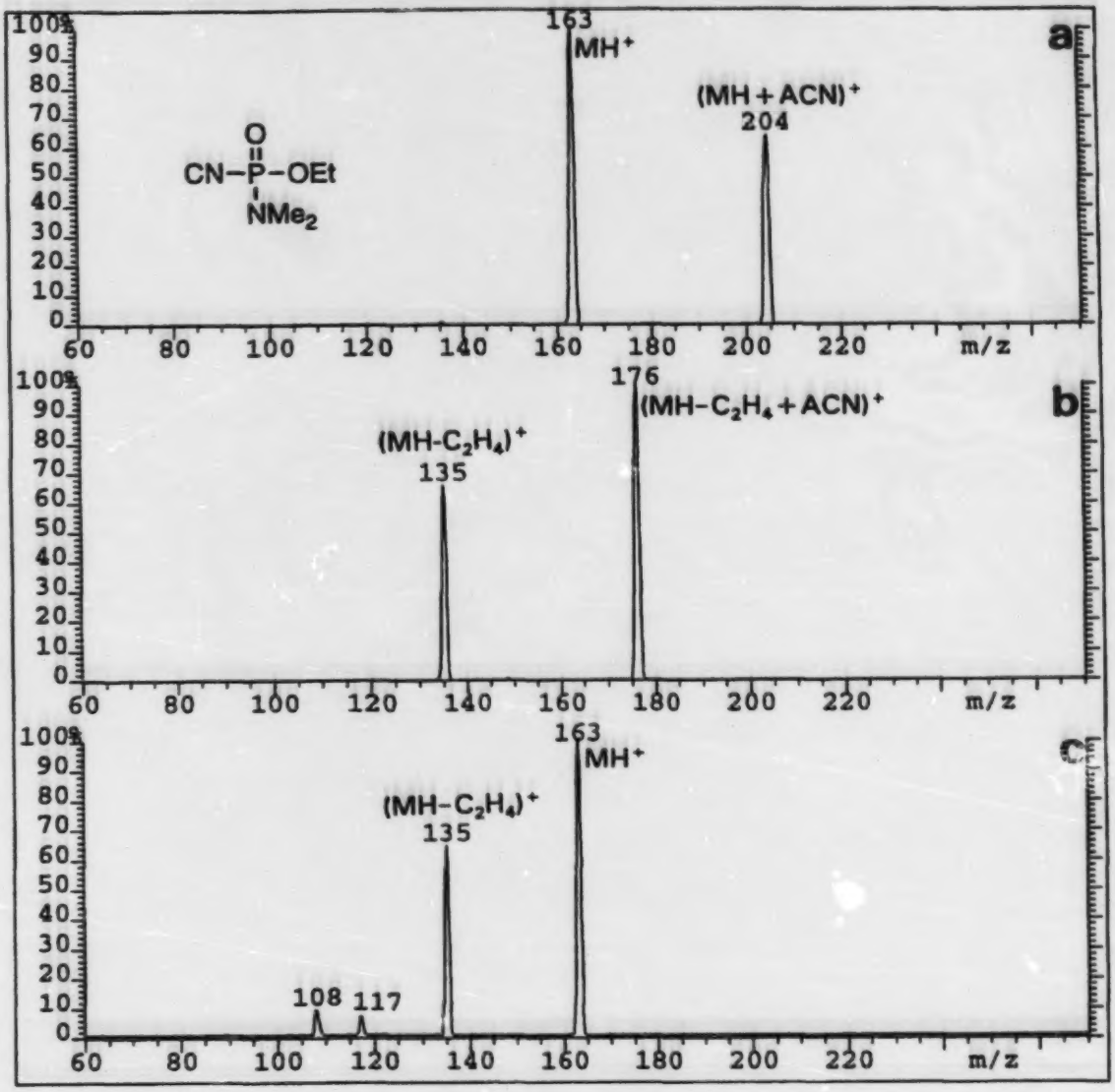

Figure 6: Product spectra for a) m/z 204, b) m/z 176 and c) m/z 163 of tabun obtained during ESI-MS/MS analysis with a quadrupole collisional cell argon pressure of 2×10^{-2} Pa (near the cell) and cell energies of 5 volts, 5 volts and 35 volts, respectively.

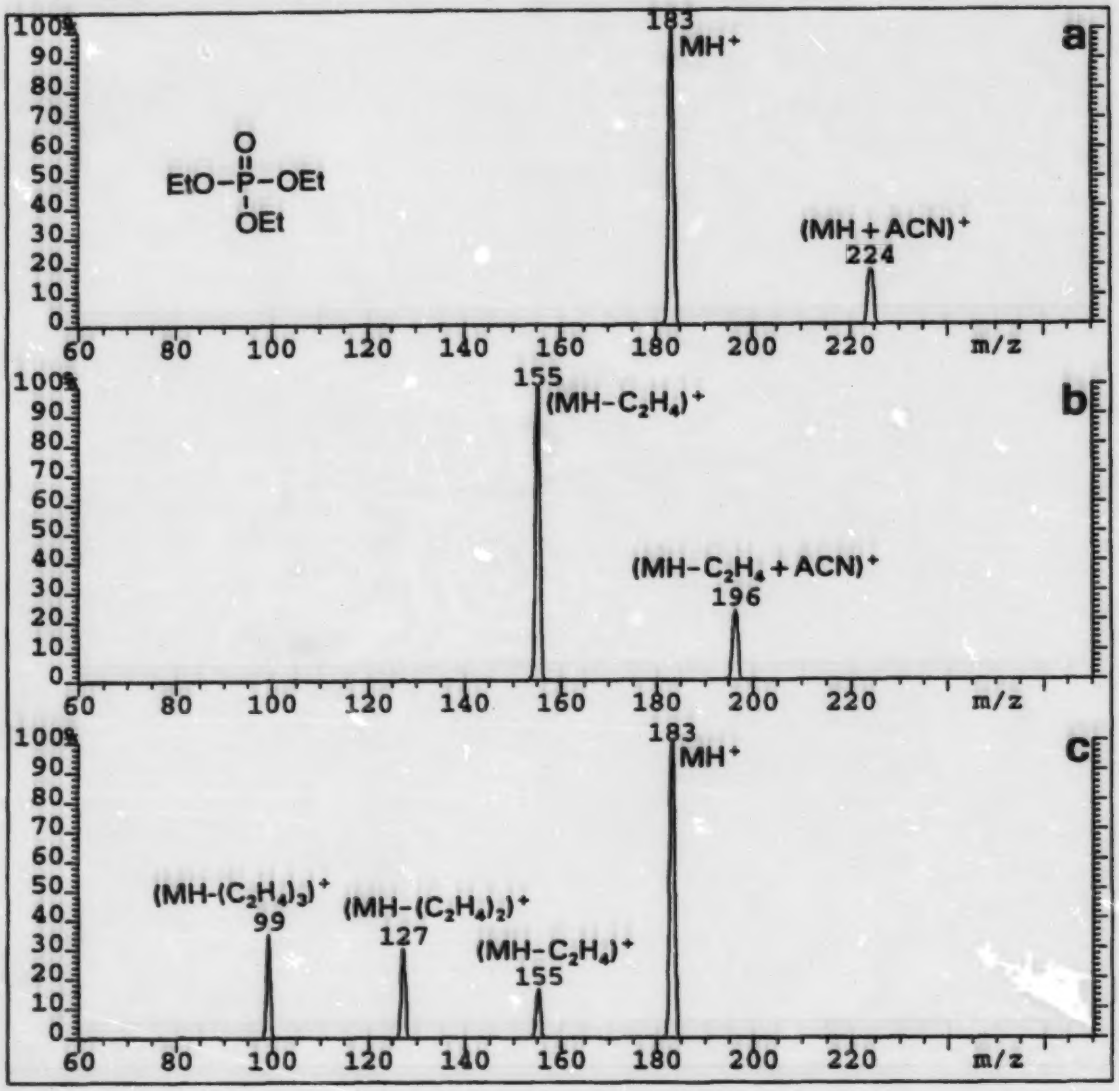

Figure 7: Product spectra for a) m/z 224, b) m/z 196 and c) m/z 183 of triethyl phosphate obtained during ESI-MS/MS analysis with a quadrupole collisional cell argon pressure of 2×10^{-2} Pa (near the cell) and cell energies of 5 volts, 5 volts and 35 volts, respectively.

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This study represents the first application of packed capillary column liquid chromatography-electrospray mass spectrometry (LC-ESI-MS) for the characterization of a munitions-grade chemical warfare agent, typical of what might be encountered during Canadian Forces (CF) sample collection. LC-ESI-MS was used for the direct analysis of nanogram quantities of tabun and eighteen related compounds in aqueous samples, extending the range of analytical options available to the researcher confronted with the identification of chemical warfare agents. Tabun and the related phosphates and pyrophosphates exhibited (M+H)+, (M+H+ACN)+ ions and/or protonated dimers that could be used to confirm the molecular mass of each compound. Product ions formed in the ESI interface were limited to those resulting from alkene loss from the alkoxy substituents (and their acetonitrile adducts). Additional product ion information were obtained following ESI-MS/MS analysis. The developed method appears to be an attractive alternative to gas chromatography-mass spectrometry (GC-MS) for the analysis of aqueous samples, since they may be analysed directly reducing the need for additional sample handling or derivatization steps.

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Tabun

G-Agent

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Mass Spectrometry

Electrospray

Tandem Mass Spectrometry

CW Detection and Identification